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Observational Probes of Dark Energy

Observational cosmology:
parameters (H_0, Ω_0) =>
evolution $(a(t), g(z,k))$

For the future: from parameter measurement => testing models

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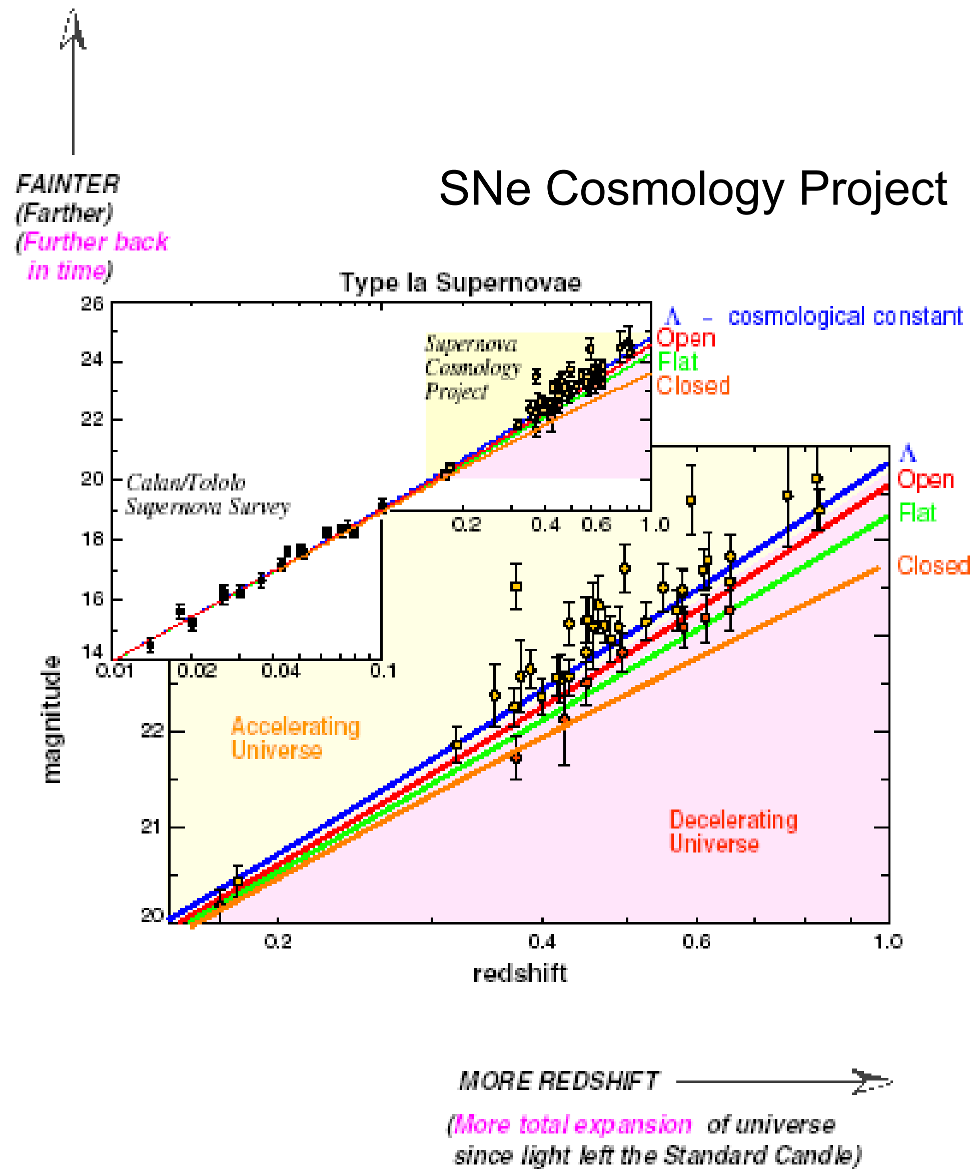
Precision cosmology

- Tools of observational cosmology have become increasingly precise
- Large, well defined, and accurately observed surveys provide samples of SNe, galaxy clusters, galaxy redshifts, quasars, Ly-α absorption lines, gravitational lenses, etc.
  - **Statistical precision is a burden**
- More careful comparison of theory to observables is required to turn precision into accuracy
- “Dark Energy” will play a key role: anomalies in the global evolution of spacetime.

=> Determining the expansion history

Current Supernova Results

- $d_L(z)$ measurements, made using type Ia SNe, provide spectacular Hubble diagrams
- These indicate an expansion rate increasing with time
- Shorthand: consistent with Λ~0.7

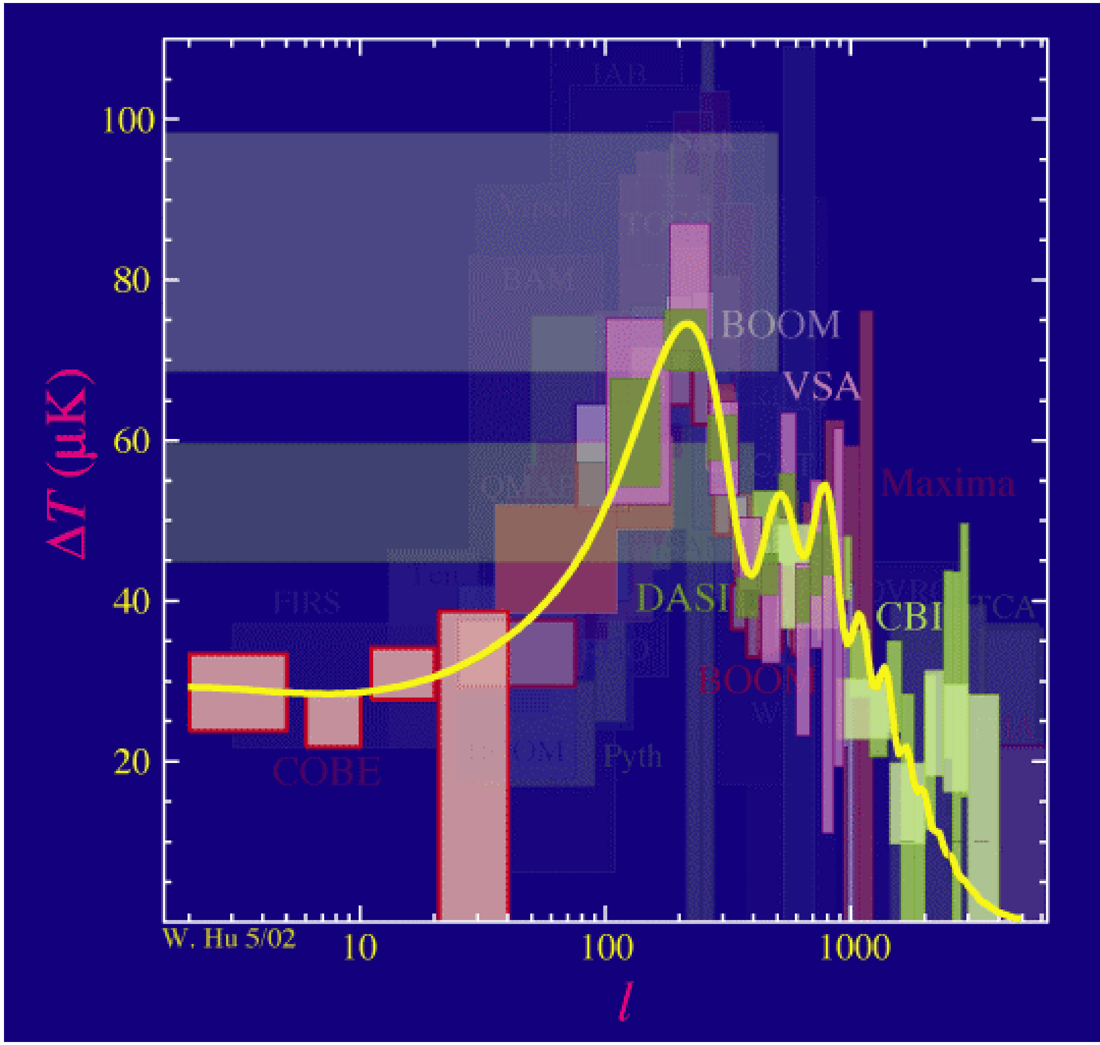


Current CMB and mass census constraints

Measurements of the first CMBR Doppler peak find Ω_{total}=1

Many measurements of clusters, baryon fractions, etc. find Ω_{matter}~0.3

Combined, these independently suggest the existence of dark energy



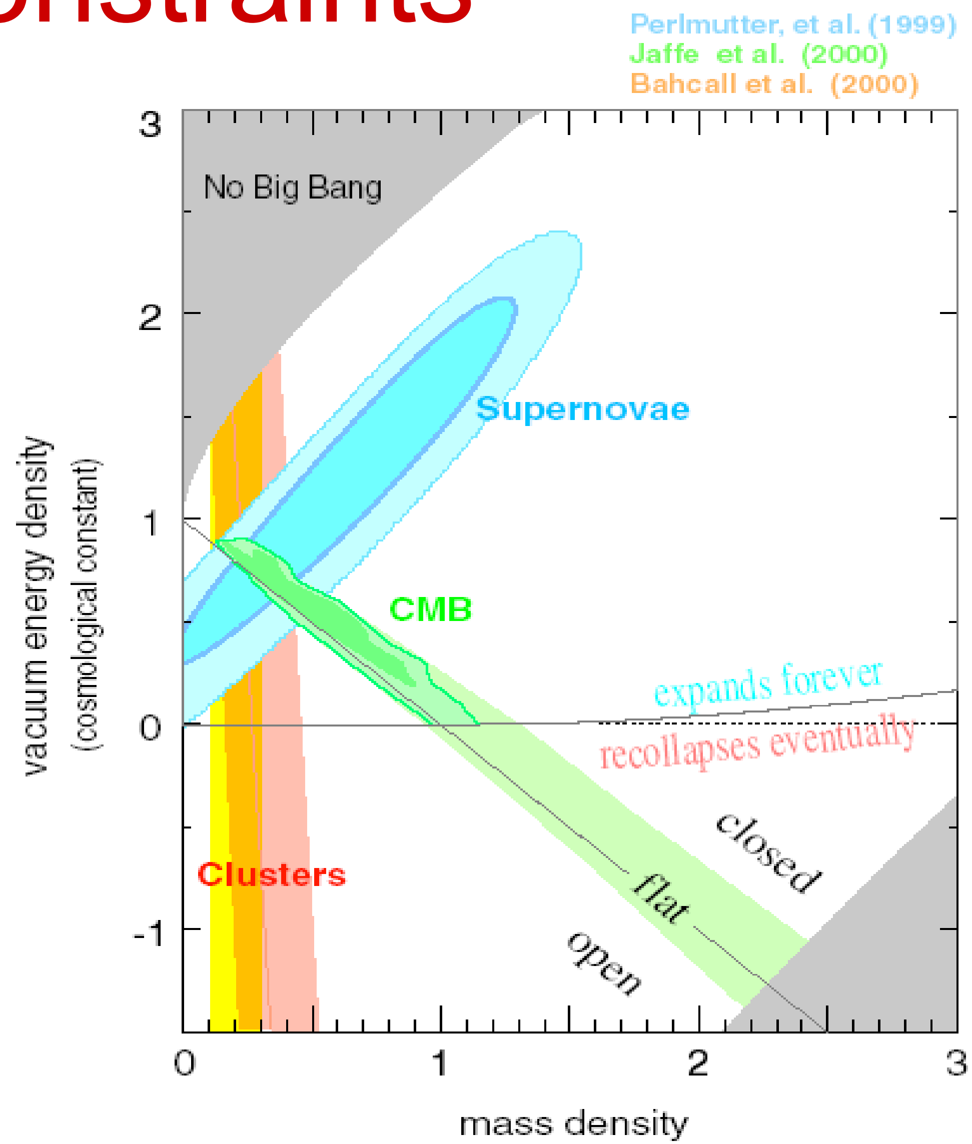
Wayne Hu: CMB data as of 5/02

Combined constraints

Convincing confirmation of anomalies in the expansion history by independent methods.

We might be able to do this!

Ignorance is large: cosmic expansion is more complex than we expected but now observationally accessible



Measuring the global spacetime

Measuring the expansion history, the expansion rate as a function of time, amounts to testing the redshift evolution of the effective density:

$$\rho_m^0 (1+z)^3 + \rho_k^0 (1+z)^2 + \rho_{DE}^0 (1+z)^{3(1+w)} = \frac{3H^2(z)}{8\pi G}$$

Most directly from cosmological distance probes:

$$d_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

Measuring fluctuations in the spacetime

In addition to the global expansion, we can study linear perturbations to the metric, the evolution of the growth factor.

The whole suite of structure formation tools: Large scale structure, galaxy clusters, weak lensing etc.

$$\delta(z,\mathbf{k}) = \frac{g(z,\mathbf{k})}{(1+z)}\delta(0;\mathbf{k})$$

Constraining the evolution of ρ_{eff}

Most observations of classical cosmology…

Distance probes:

1. CMB acoustic peaks
2. Type Ia Supernovae
3. SZ + X-ray observations of clusters
4. Strong lensing statistics
5. Ly-α forest cross-correlations
6. Alcock-Paczynski test
7. Galaxy counts (volume element)

SNe standard candle experiments as an example

Observational Probes 2: g(z,k)

Probes of the growth of structure:

1. CMBR
2. Weak lensing (esp. with tomography)
3. Galaxy clusters
4. Ly-α forest (at high z)
5. Galaxy redshift surveys (z < 1)

Issues facing galaxy cluster studies

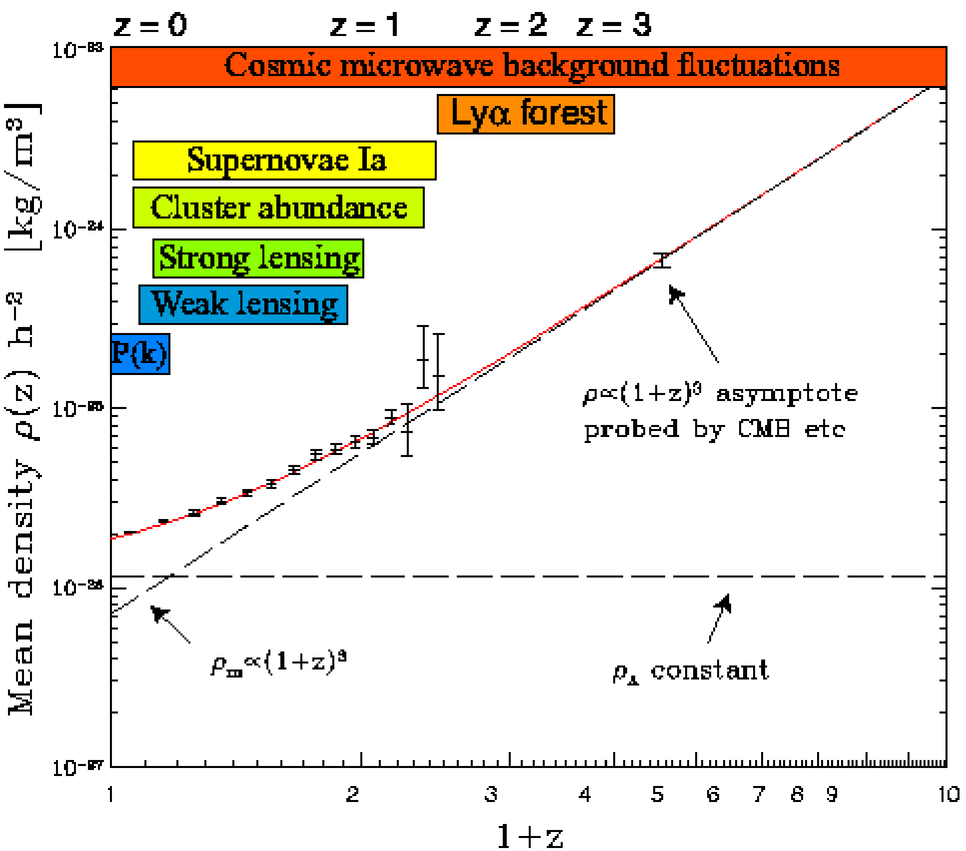
What are the limitations?

Criteria for comparison:

- How closely do the observables relate to theory?
  - True standard candle => d_L is great
  - Abell richness => mass is poor
- How precisely can each observable, in practice and in principle, be measured?
  - SZ decrement from high-z clusters is great
  - Ly-α forest at low redshift is very hard
  - Cosmic variance, projection effect noise in lensing….
- How mature is each method? To what extent has the list of possible limitations been faced and overcome?

At what redshifts should we probe?

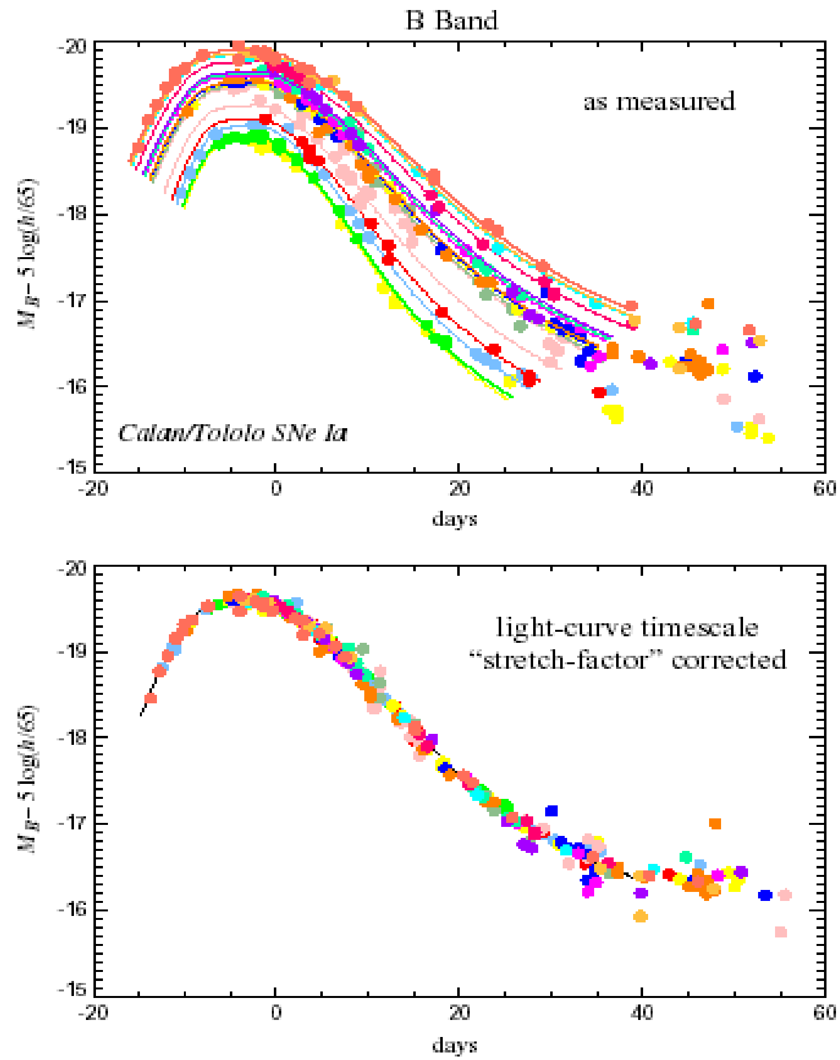
- Effect of dark energy becomes apparent at late times
- Expansion passes from decelerating to accelerating
- Effective density asymptotes to vacuum contribution
- DE is apparent at z < 3



Tegmark: astroph/0101354

Type Ia Supernovae

- Type Ia's are proven 'standardizable' candles
- Stretch factor related to amount on Ni in explosion
- Achievable dispersion in peak luminosity ~10%: measures d_L vs. z



Kim, *et al.* (1997)

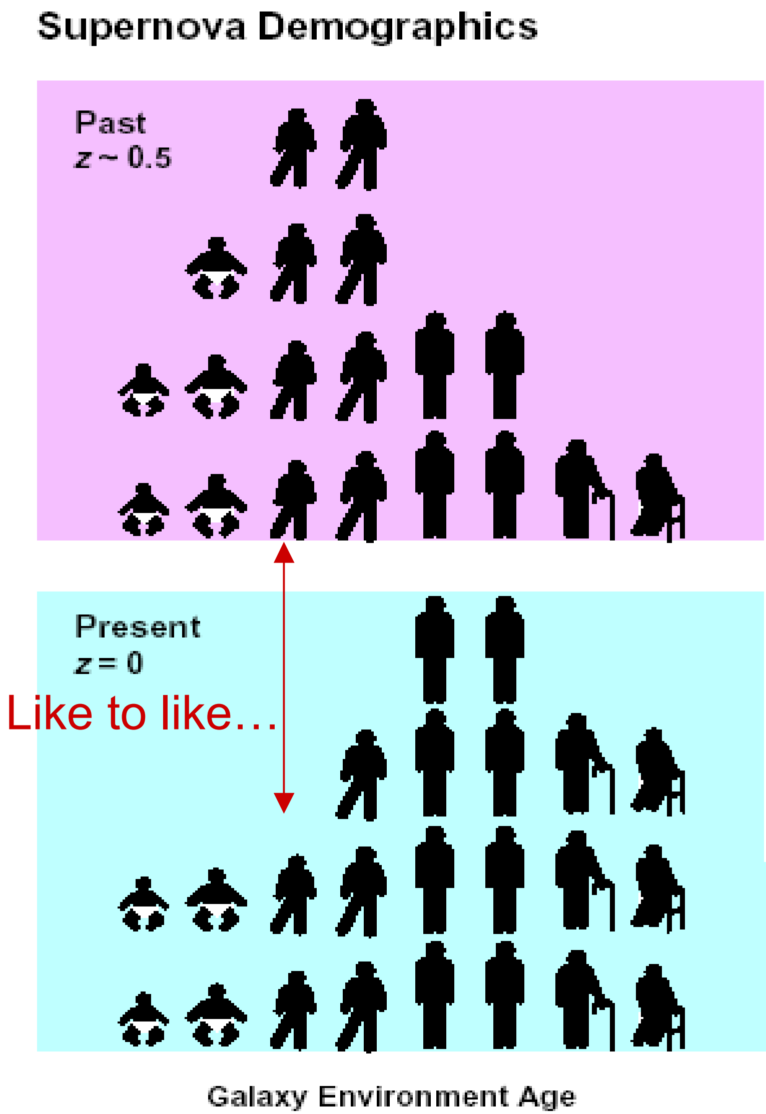
Extending the SNe results:
A wide variety of concerns

- Evolution of the SNe population
  - Drift in mean metallicity, mass, C-O
  - Variation in mean SNe physics parameters: distribution and amount of Ni, KE, etc.
- Gravitational lensing magnification
- Dust
  - Normal
  - Clumpy or ~homogeneous grey
  - Galactic extinction
- Observational biases
  - Malmquist
  - K correction, calibration, and color tems
  - Contamination by non-Ia explosions

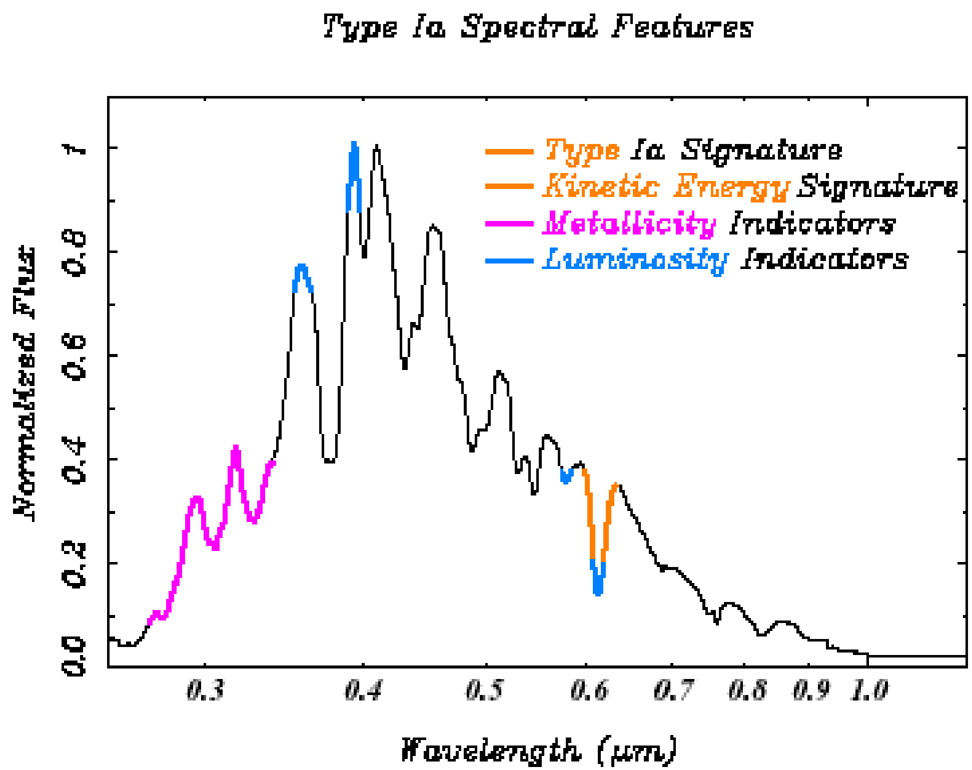
SNe observations internally provide ways to check all of these: e.g. **SNAP**

SNAP material from Saul Perlmutter

SNe evolution: all ages are found at every redshift



SN are phenomenologically rich, full of diagnostics

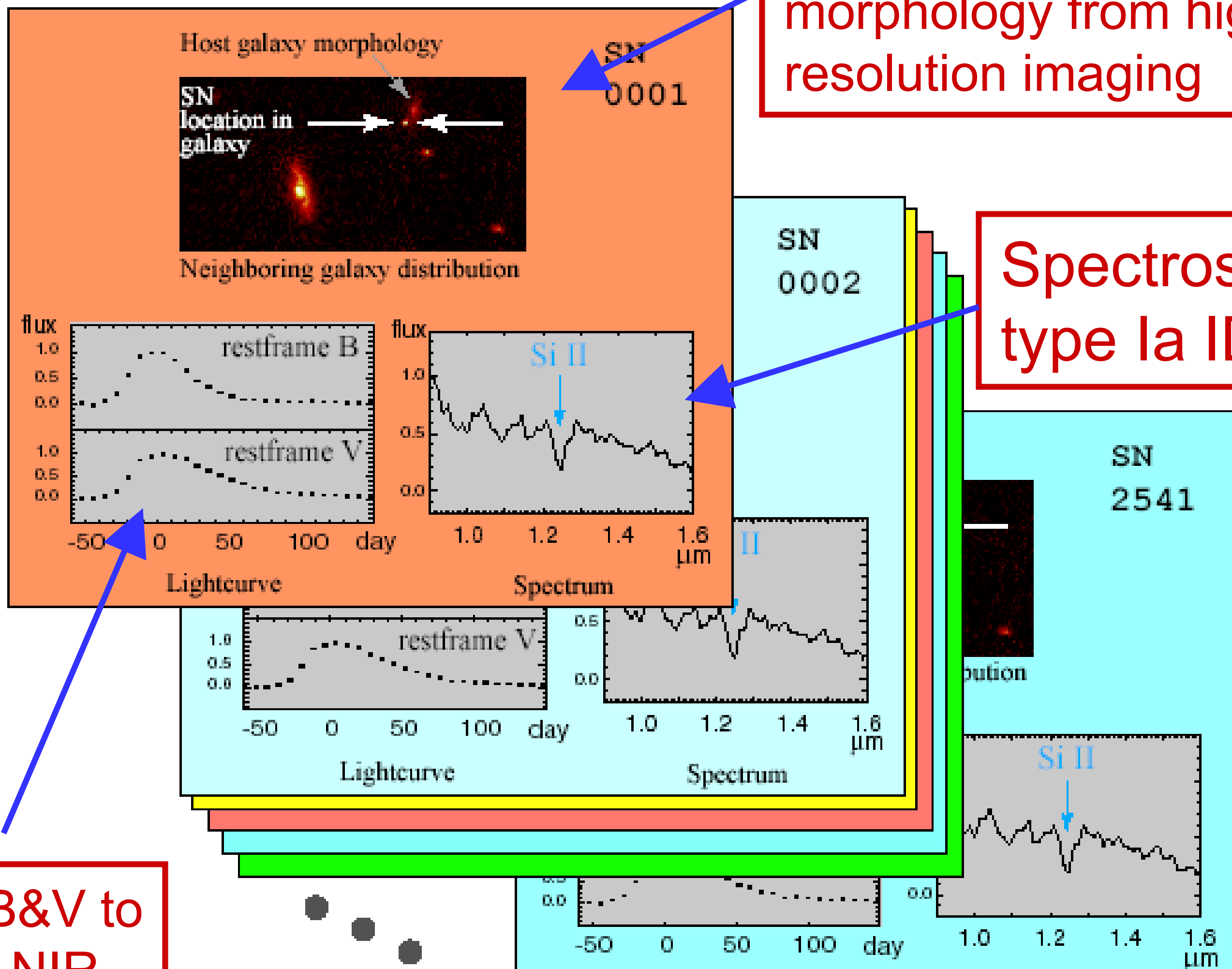


Light curves and spectra provide an effective fingerprint

Extensive information for each SNe is essential!

Host galaxy morphology from high resolution imaging

Spectroscopic type Ia ID etc.



Restframe B&V to z=1.7 using NIR

SNAP can provide this kind of data

Sort into closely defined classes: Compare like to like *only*

1

Sort into Like Subsets

Group A:
* Si II in spectrum: type Ia
* elliptical host
* bright UV: low metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities
9000 < v < 10000 km/s

Group B:
* Si II in spectrum: type Ia
* in core of late-type spiral host
* faint UV: high metallicity
* fast rise time: low Ni56 mass
* spectral feature velocities
9000 < v < 10000 km/s

Group C:
* Si II in spectrum: type Ia
* in outskirts of late-type spiral host
* bright UV: low metallicity
* long rise time: high Ni56 mass
* spectral feature velocities
8000 < v < 9500 km/s

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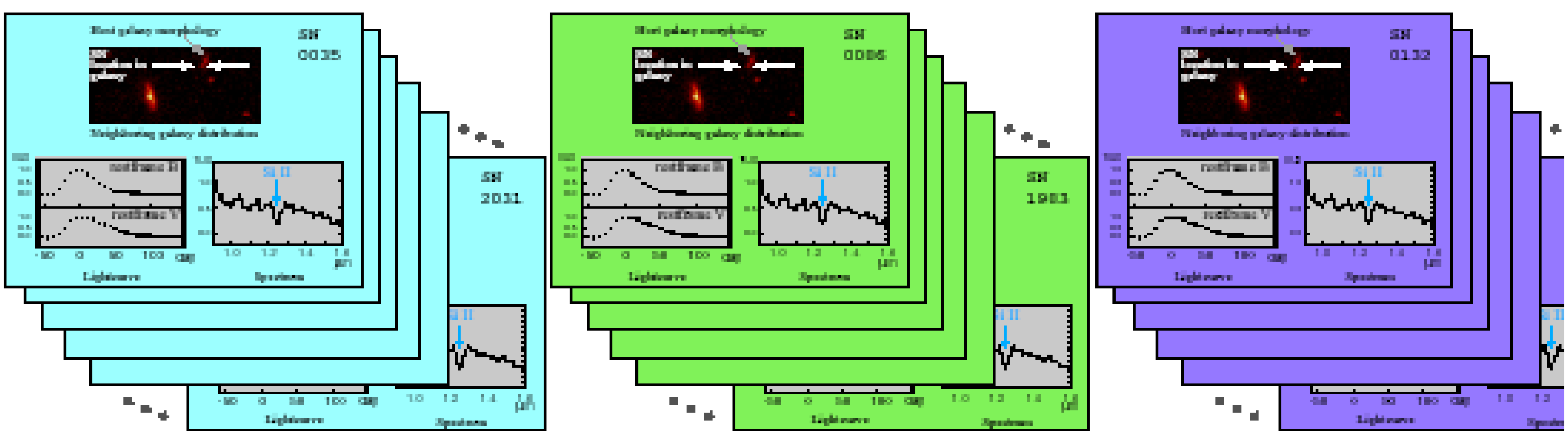
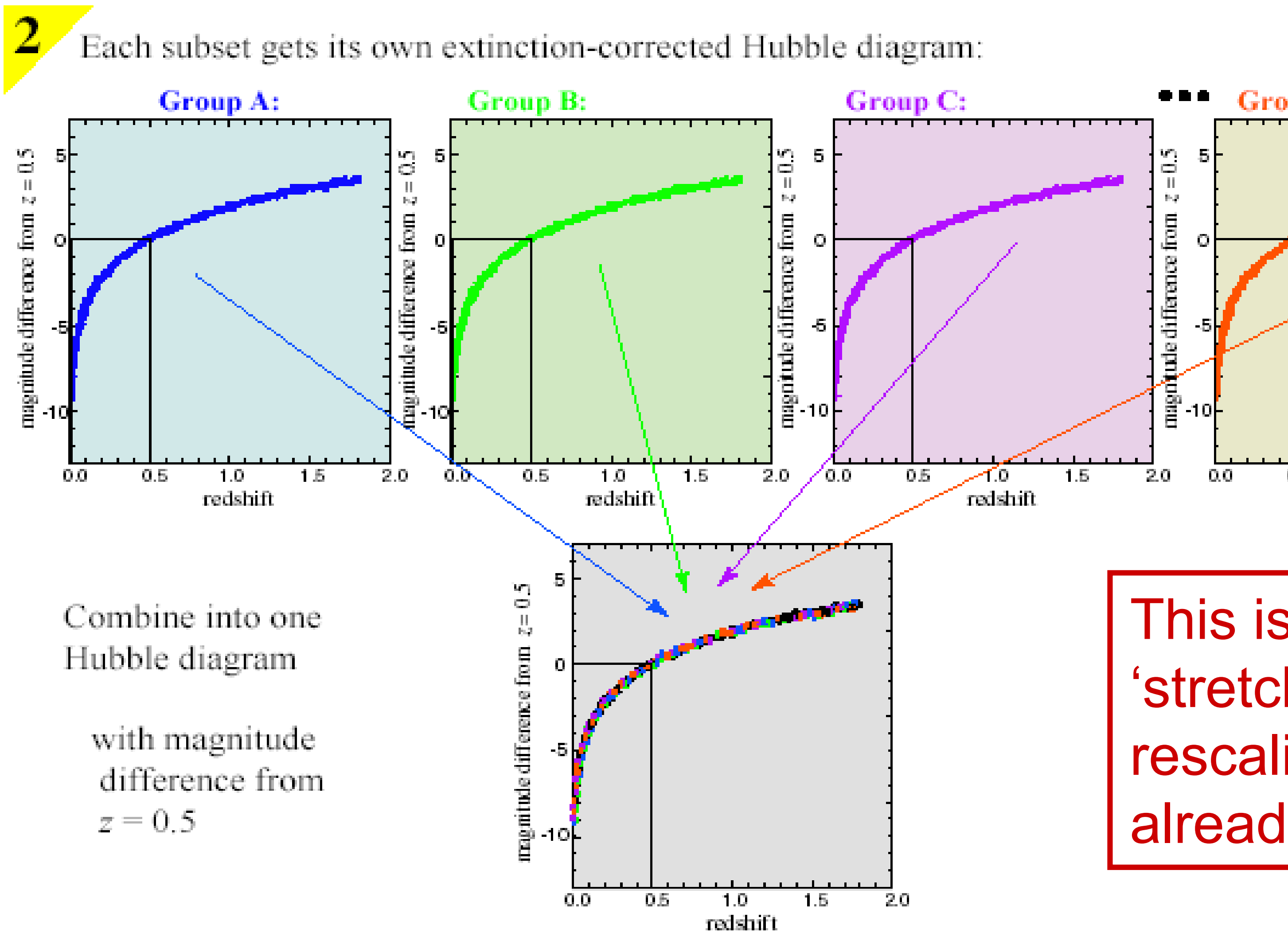


Construct a Hubble diagram for each class

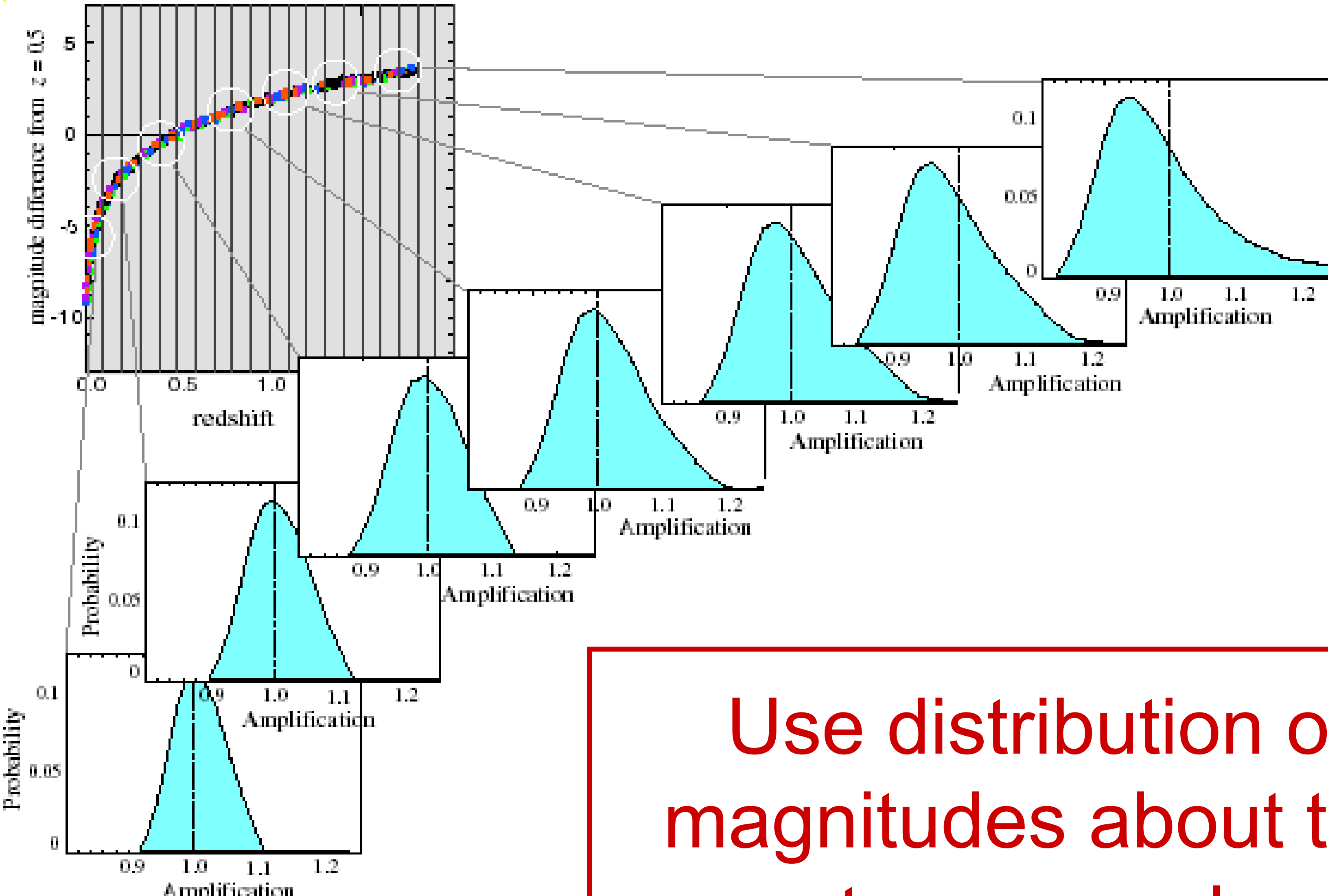
Allows for variations in true peak brightness between classes



This is really what ‘stretch factor’ rescaling is already doing.

3

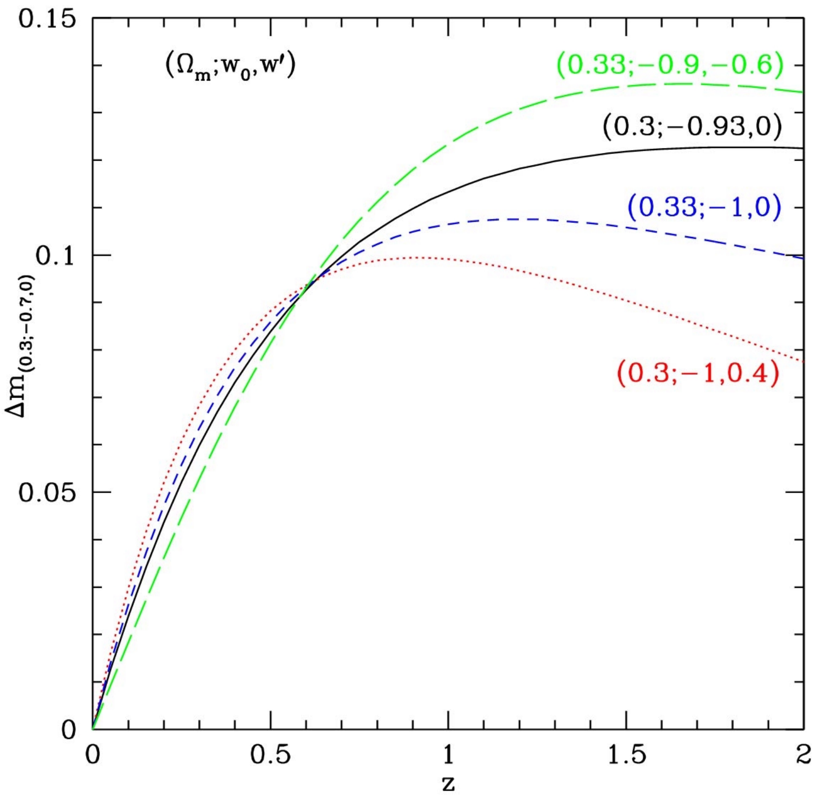
Break Hubble diagram into slices to look at lensing distributions



Use distribution of magnitudes about the mean to remove lensing

Evolution to high redshift may prove key

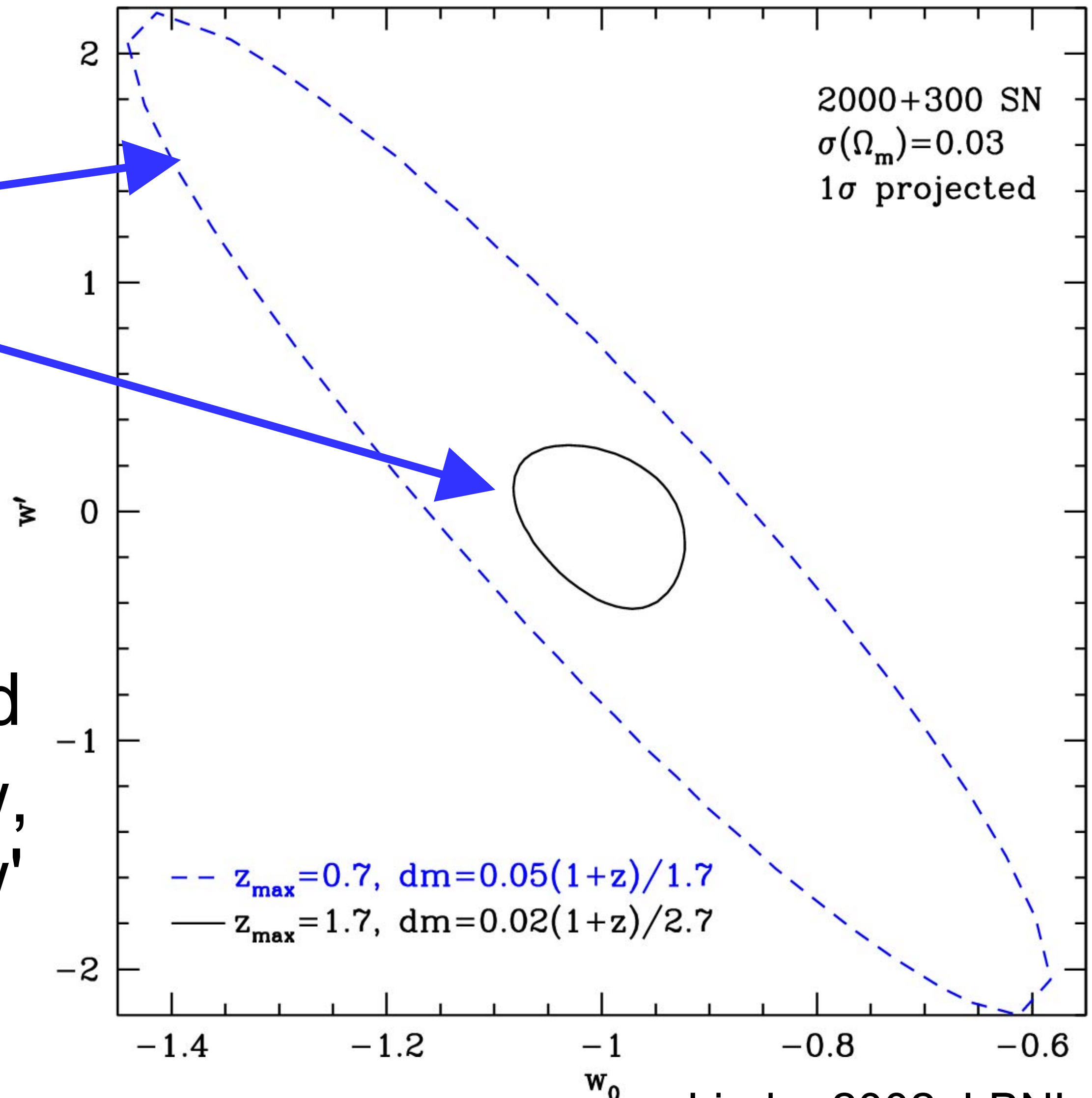
- Degeneracies in models are reduced as the redshift range increases.
- Studies at z<1 can tell us *that* dark energy exists, but can't say much about *what* dark energy is.



Eric Linder: LBNL

SNe can achieve real model constraints

- Assume SNAP
- ~2000 SNe to z=0.7 and to z=1.7
- Each observed precisely enough to fill in its datasheet
- Known systematic uncertainties included
- 10% constraints on w, 30% constraints on w'



Linder 2002: LBNL

Galaxy cluster surveys

- Probing growth of linear perturbations by measuring the space density of the largest peaks
- Analytic theory and N-body simulations predict dn/dM as a function of z
- Cosmology comes from *comparison* of observed dn/dM vs. z to theory

Cluster detection measures something other than mass: observables like SZ decrement, X-ray flux, galaxy σ_v, shear…..

To approach dn/dM vs. z we need to know:

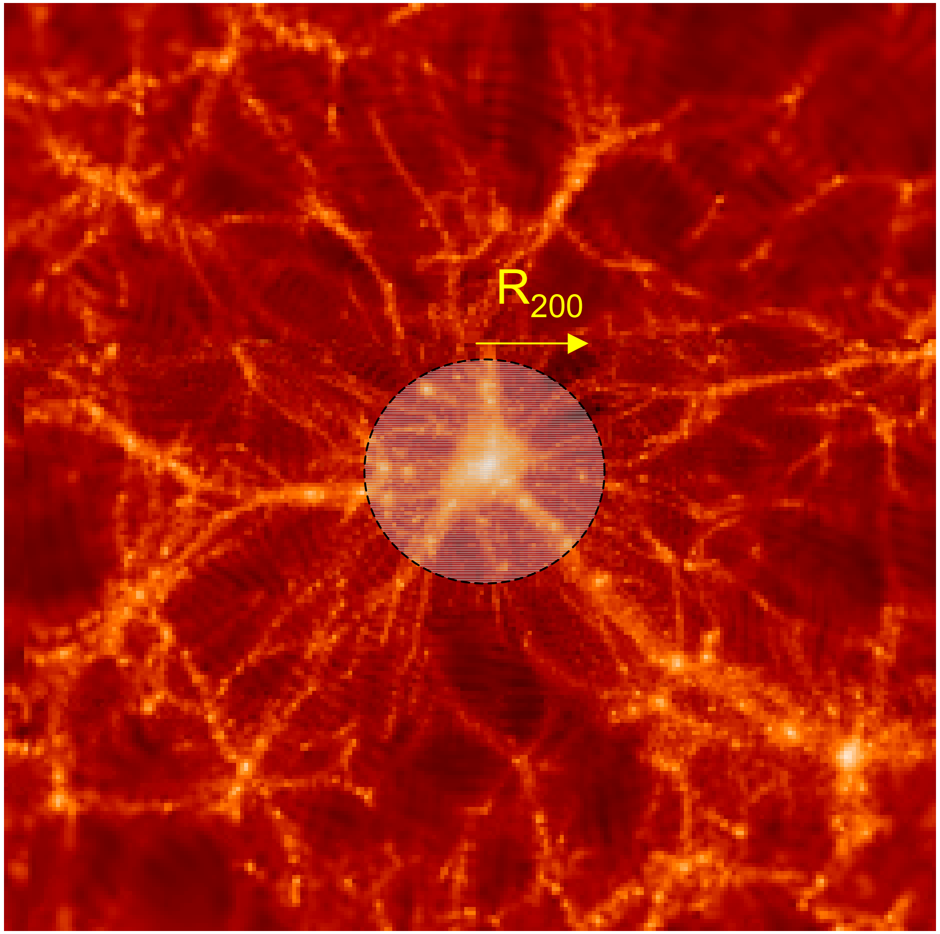
M(observables,z)

Efficiency(observables, z)

The mass function is very steep!

What is a cluster for theorists?

- A large peak in the dark matter density
- Mass defined (for example) as total mass within R_{200}, where mean overdensity is 200 times the critical density => M_{200}

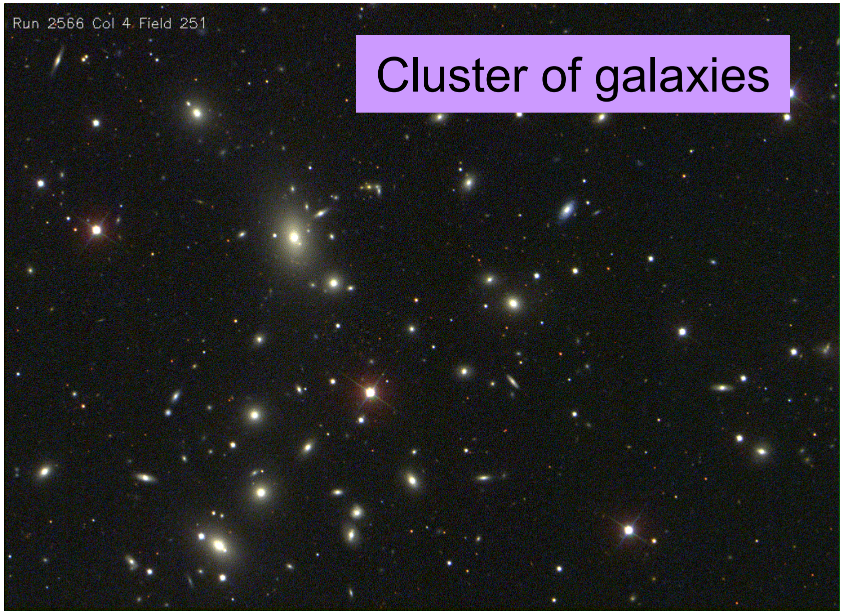


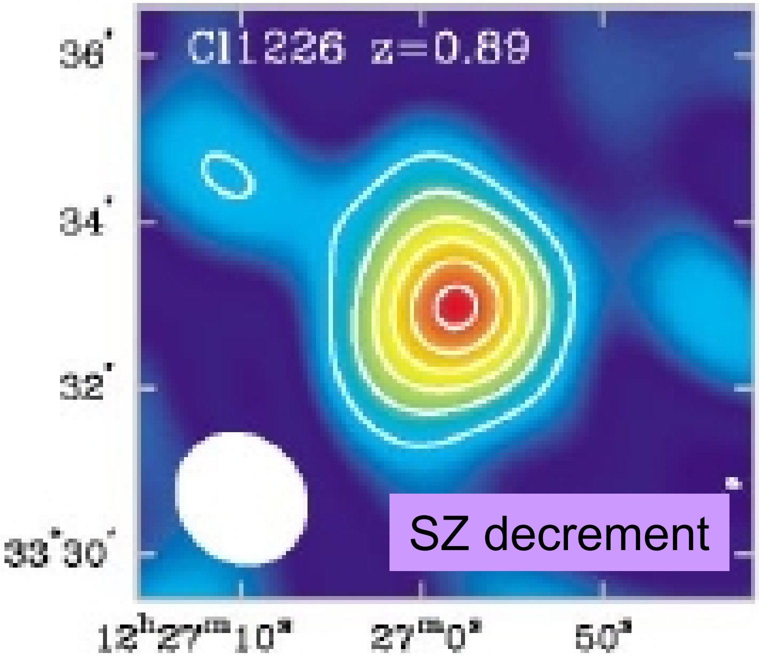
Springel et al. 2001

What is a cluster for observers?

Large peak in matter density

- Dark matter clump (~80% of mass)
- Many luminous galaxies (~2%: 10% of baryons)
  - BCG and red sequence
  - Additional galaxies
  - Diffuse light
- Hot gas (~18%: 90% of baryons)
  - Emits X-rays
  - Causes SZ decrement in microwave background





Carlstrom et al. 2002

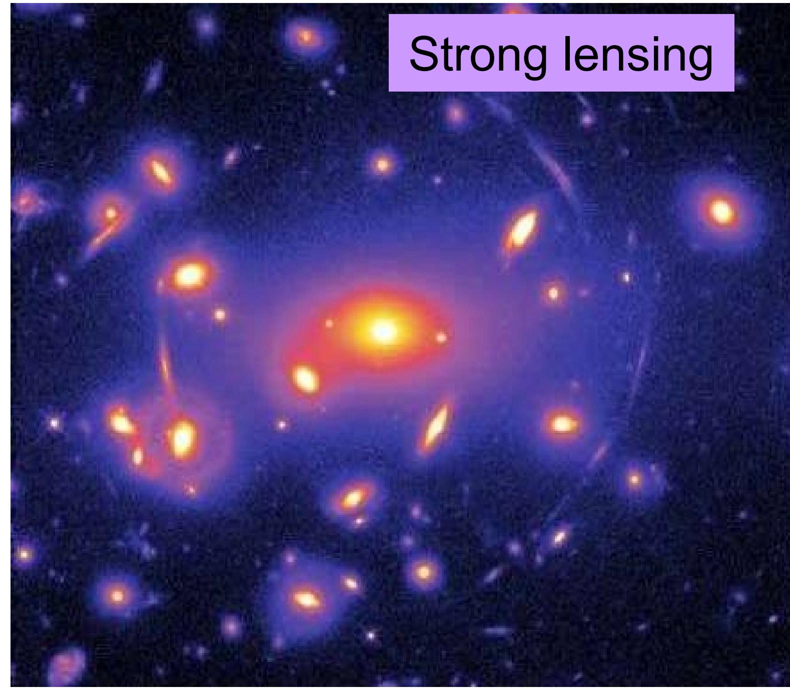
Estimating mass in observers clusters

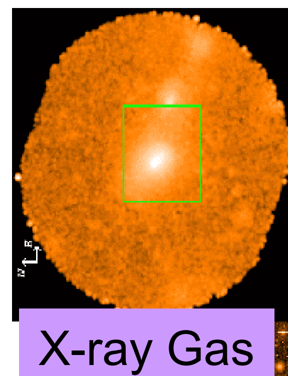
- Clusters of galaxies: galaxy richness, luminosity, velocity dispersion
- Clusters of hot gas: X-ray flux, temperature, SZ decrement
- Clusters of projected mass: strong lens geometry, weak lensing shear

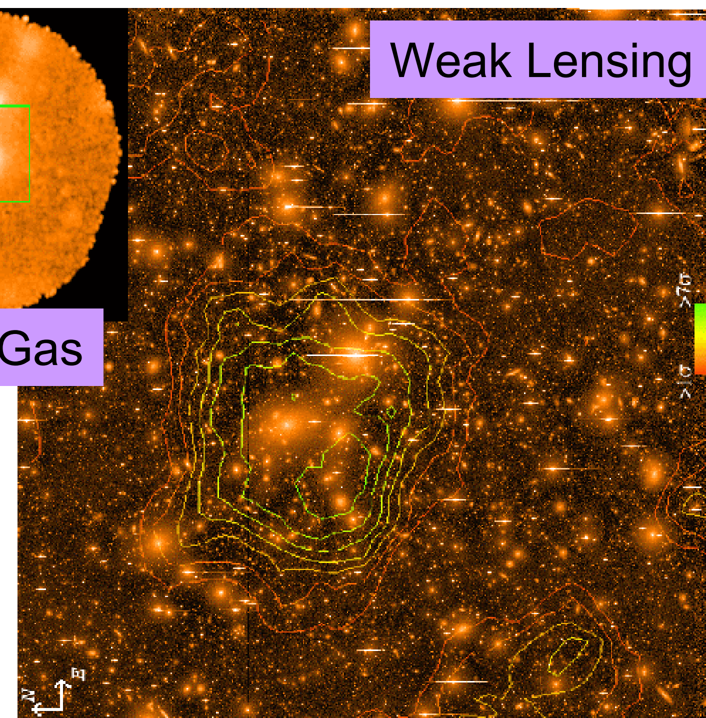
How to find R_{200} and M_{200} without loose assumptions…

Two approaches:

1. Learn the astrophysics to understand M=f(observable,z)
2. Learn to predict dn/d(observable,z) instead of dn/dM







Analogy to SNe

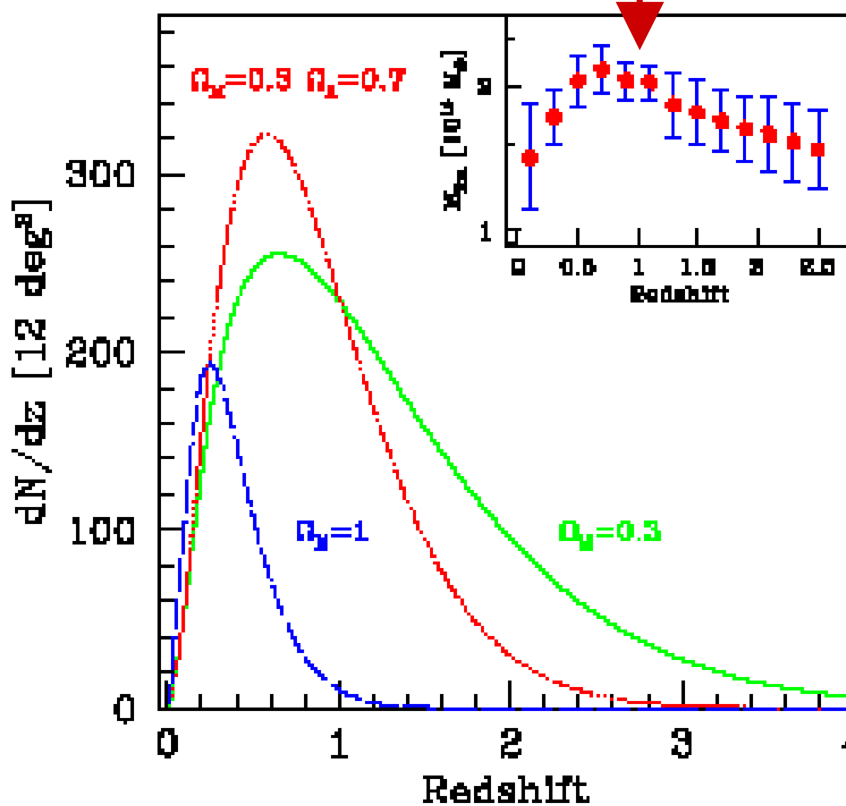
For SNe, we want to know luminosity: measure spectrum, stretch, rise time, extinction, peak to tail ratio etc….

For clusters, we want to know mass: measure SZe, F_x, T_x, σ_{gal}, lensing, N_{gal}, etc.

Massive cluster surveys are coming

- 2DF and SDSS 3D surveys (~10^3 to z~0.15)
- SDSS 2.5D photo-z surveys (~10^5 to z~0.5)
- SZ surveys: SZA, SPT, AMiBA, etc.
- Lensing surveys from Legacy, LSST, and SNAP

Fantastic sensitivity to high redshift!



Joy and Carlstrom: Science

Cluster surveys: in their childhood

- Clusters make great cosmological probes
  - Very detectable
  - Evolution is approachable
  - Sensitive (exponential) dependence on cosmology
- Clusters are complex: we must understand them better to use them for cosmology
- We need to observe and model clusters in their full richness to test our understanding
- We need to count all clusters:
  - absolute efficiency required
  - fundamentally a Poisson limited process (cosmic variance)

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Conclusions

- Tremendous new observational prospects
  - Optical SNe and lensing surveys on ground and in space
  - SZ surveys
  - CMB anisotropy and polarization
- Completing these will require serious support and high priority
- Interpreting these observations accurately will require extensive new modeling efforts

Run 3031 Col 5 Field 449

A wish list

1. Care in comparisons between observation and theory
2. Enhance support for serious new observational programs: no reason to wait
3. Coordination of observational programs: independent studies of structure are less helpful
4. Coordination between observers and modelers: N-body simulations => ‘observable’ simulations

Now is the time to study expansion history